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RAY TRACING OF JOVIAN KILOMETRIC RADIATION

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Abstract. Results of computer ray tracing of Jovian kilometric radiation from 56.2 kHz to 1 MHz in a model Jovian magnetosphere with an Io torus are presented. Ray tracing calculations indicate that the Io torus presents a propagation barrier to the radiation and that the Jovian kilometric radiation must be generated in the L-O mode from a source near Jupiter on field lines passing through the Io torus. One effect of the Io torus is to refract the rays away from the magnetic equator forming a shadow zone at radial distances beyond the torus. In general, at radial distances greater than 10 Jovian radii, as the wave frequency increases (> 200 kHz) so does the magnetic latitude of the shadow zone. These and other features of the ray tracing calculations are in good qualitative agreement with the observations from the plasma wave receiver and planetary radio astronomy experiment on board both Voyagers 1 and 2.

Introduction

One of the many interesting discoveries made by Voyagers 1 and 2 on their recent flyby of Jupiter was the detection of intense radio emissions at kilometric wavelengths. The frequency spectrum of Jovian kilometric radiation has been observed to extend from frequencies as low as 10 kHz (see *Scarf et al.* [1979]) to as high as 1 MHz [*Warwick et al.*, 1979]. The duration of the kilometric bursts is a function of frequency with a decreasing duration at higher frequencies, giving the emissions a tapered appearance in a frequency-time spectrogram.

The purpose of this paper is to present initial ray tracing calculations which reproduce the basic characteristics of Jovian kilometric radiation observed by Voyagers 1 and 2. The calculations explain the tapered appearance of the kilometric radiation as a propagation effect produced by the Io torus. The good agreement with the observations supports the view that the Jovian kilometric radiation is generated in the L-O mode above the local electron plasma frequency from source regions near Jupiter on field lines which pass through the Io torus. Predictions of the shape and polarization of the kilometric radiation spectrum as would be observed by Voyager 1 near periapsis are also presented based entirely on the ray tracing calculations.

The Model Jovian Magnetosphere

The computer ray tracing program used in this study is identical with that used by *Green et al.* [1977] for ray tracing of the Earth's auroral kilometric radiation with the exception of the substitution of a Jovian model magnetosphere (subroutine) for that of the Earth. Further description of the computer program can be found in *Green et al.* [1977].

The model Jovian magnetosphere used in this study is shown in the top panel of Figure 1 as contours of the electron plasma frequency in kilohertz. The plasma frequency contours are a combination of the models proposed by *Sentman and Goertz* [1978] and *Warwick et al.* [1979]. Away from the Io torus the electron density is a smooth approximation to the Pioneer 10 density measurements at radial distances $> 3\ R_J$ as reported by *Frank et al.* [1976]. Near the Io torus the electron plasma frequency contours were determined by a spline interpolation fit to the torus densities determined by *Warwick et al.* [1979] from Voyager 1 observations. The validity of this Jovian magnetospheric model is confirmed by the excellent agreement between the ray tracing calculations of *Menietti and Gurnett* [1980] and the observed dispersion of whistlers detected by Voyager 1 [*Gurnett et al.*, 1979c]. All plasma frequency contours in Figure 1 are assumed to be symmetric about the magnetic equator. The Jovian magnetic field model used consists of a magnetic dipole with a moment of 4.225 gauss R^3_J. The dashed line in the top panel of Figure 1 is an L=6 magnetic field line representative of the dipole model used in this study.

Location of the Source Region

It is most likely that the source region for the Jovian kilometric radiation is located on field lines where auroral particle precipitation and field-aligned currents occur since the Earth's auroral kilometric radiation has been correlated with auroral particle precipitation and field-aligned currents (see *Green et al.* [1979a,b]). In the Jovian magnetosphere a possible source region may be along the magnetic field lines through the Io torus where intense charged particle precipitation has been inferred from ultraviolet auroral emissions (see *Broadfoot et al.* [1979]) and field-aligned currents are indicated by low frequency auroral hiss measurements (see *Gurnett et al.* [1979a]).

Two modes of propagation, the left-hand ordinary (L-O) and right-hand extraordinary (R-X), must be considered for the Jovian kilometric radiation. The lower frequency cutoffs for the L-O and R-X polarized modes of propagation are the electron

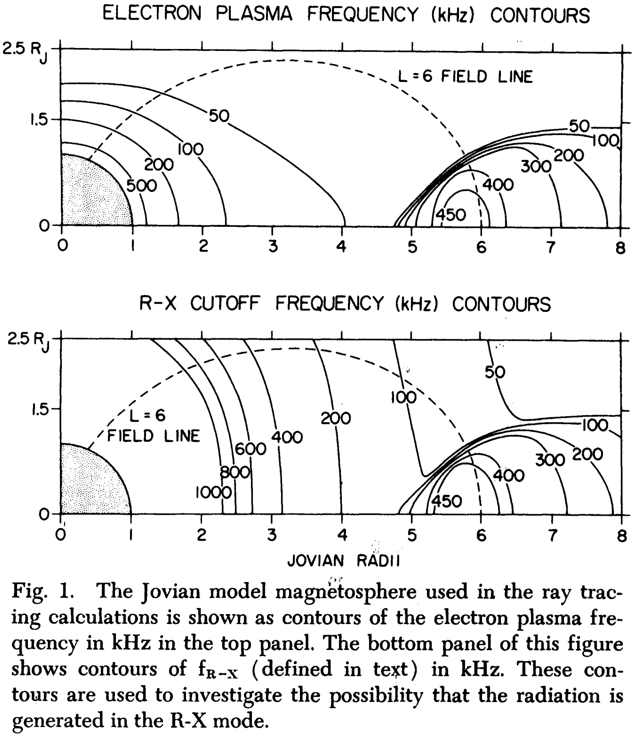

Fig. 1. The Jovian model magnetosphere used in the ray tracing calculations is shown as contours of the electron plasma frequency in kHz in the top panel. The bottom panel of this figure shows contours of f_{R-X} (defined in text) in kHz. These contours are used to investigate the possibility that the radiation is generated in the R-X mode.

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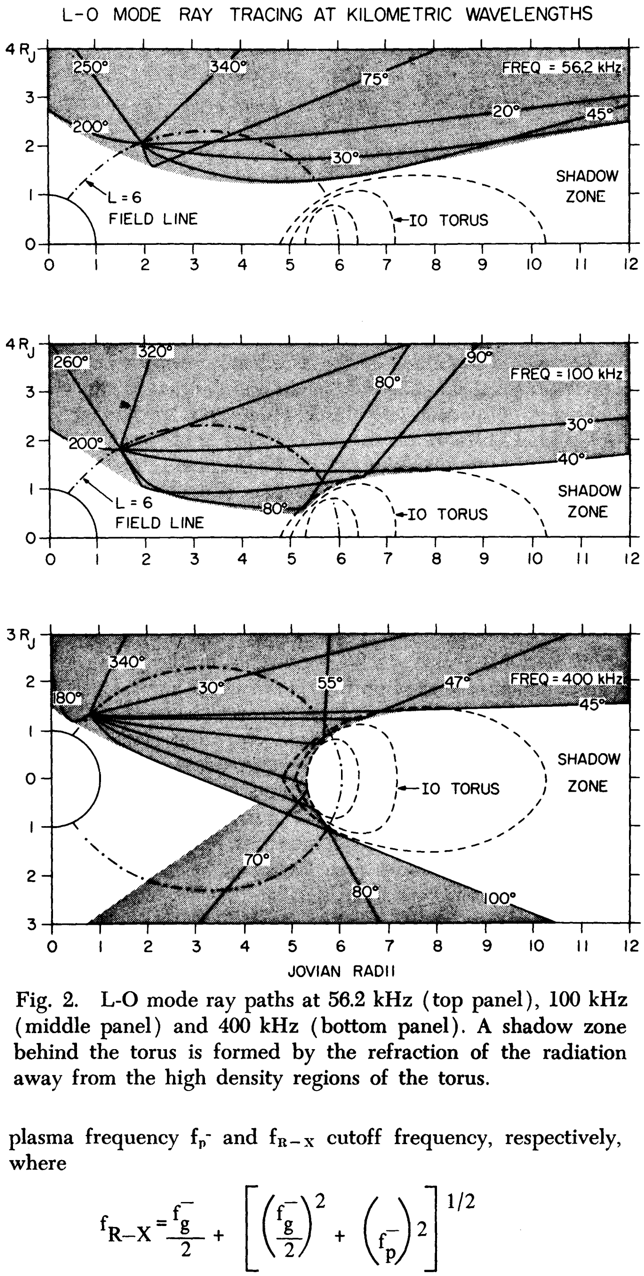

Fig. 2. L-O mode ray paths at 56.2 kHz (top panel), 100 kHz (middle panel) and 400 kHz (bottom panel). A shadow zone behind the torus is formed by the refraction of the radiation away from the high density regions of the torus.

plasma frequency f_p^- and f_{R-X} cutoff frequency, respectively, where

$$f_{R-X} = \frac{f_g^-}{2} + \left[\left(\frac{f_g^-}{2}\right)^2 + \left(f_p^-\right)^2\right]^{1/2}$$

and f_g^- is the local electron gyrofrequency. All sources of radiation in the R-X (or L-O) mode must be located in regions where the local f_{R-X} (or f_p^-) frequency is less than the wave frequency. Contours of f_{R-X} (in kHz) in the Jovian magnetospheric model are shown in the bottom panel of Figure 1.

Observations of Jovian kilometric radiation from Voyager 1 as reported by *Scarf et al.* [1979] indicate that the radiation has been detected to as low as 10 kHz. Since the minimum value of f_{R-X} along the magnetic field lines which pass through the Io torus is much larger than 10 kHz, we can conclude that the Jovian kilometric radiation cannot be generated in the R-X mode, if it is in fact associated with the Io torus.

Warwick et al. [1979] have reported that the measured polarization of Jovian kilometric radiation is predominately left-hand when observed at high magnetic northern latitudes at large radial distances. Care must be taken when inferring the mode of propagation in the source region from polarization measurements. The determination of the mode of propagation depends upon the direction of rotation of the electric field about the ambient magnetic field in the source region. However, at large radial distances from the source, a wave's polarization is determined by the rotation direction of the electric field about the propagation vector and is no longer simply related to the polarization in the source region. Since the magnetic moment of Jupiter is directed northward the left-hand polarization measurements in the northern hemisphere tend to favor the L-O mode, if the radiation is generated near the planet in agreement with our conclusions based on the R-X cutoff frequency. Based on these preliminary considerations this study will only consider L-O mode waves since this polarization appears to be the most likely propagation mode for the generation of Jovian kilometric radiation.

If Jovian kilometric radiation is generated in the L-O mode along the field lines through the Io torus, then specific generation mechanisms must be considered in order to determine the exact location of the source regions as a function of the emission frequency. In the L-O mode the possible emission frequencies where one would expect radiation are f_{UHR} (upper hybrid resonance frequency), $2f_{UHR}$, f_p^-, and $2f_p^-$. Radiation at f_{UHR} and $2f_{UHR}$ occurs at frequencies too high to be considered since $f_{UHR} > f_{R-X}$. Radiation at f_p^- would result in a very narrow beam width which is not consistent with the observations. Emission at $2f_p^-$ is therefore considered the most likely mechanism and will be used in this initial ray tracing analysis. As will be shown the use of the $2f_p^-$ generation mechanism as a model for locating the source is not particularly critical to the results of this study since the Io torus is mainly responsible for controlling the ray paths, independent of the details of the emission mechanism.

Ray Tracing Results

All ray tracing calculations are done in a magnetic meridian plane. The source regions considered are point sources along the L=6 field line with the wave frequency at the source equal to twice the local electron plasma frequency. In addition, to avoid specific details of any generation mechanism (such as beaming) each source is assumed to emit L-O mode electromagnetic radiation in all directions (all wave normal angles) with respect to the Jovian magnetic field vector in the source region.

The computed ray paths and resulting angular distributions for 56.2 kHz (top panel), 100 kHz (middle panel) and 400 kHz radiation (bottom panel) from northern hemisphere sources are shown in Figure 2. Each ray is labelled and identified by its initial wave normal angle. The shaded regions are the total illumination patterns for each source. The wave normal angles shown include those which give the most extreme latitudinal limits to the ray paths, as well as other rays launched at intermediate directions. For reference, several contours of the electron plasma frequency near the Io torus (from Figure 1) are shown as dashed lines in Figure 2.

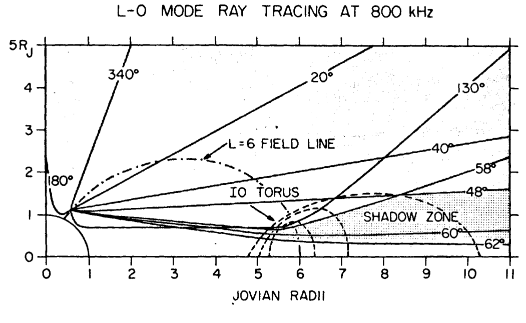

Fig. 3. This figure (L-O mode ray tracing at 800 kHz) illustrates the effect the Io torus has on high frequency $\gtrsim 500$ kHz ray paths. Not only does the torus have a tendency for wave refraction away from the magnetic equator, but at certain initial wave normal angles the torus is transparent, refracting rays at low latitudes along the magnetic equator.

Figure 2 illustrates the basic ray path effects at frequencies from 56.2 kHz to nearly 500 kHz. For this frequency range the effect of the Io torus is to refract all the rays away from the magnetic equator forming a shadow zone at radial distances beyond the torus. Note that at 100 kHz and 400 kHz (middle and bottom panels) a beam as large as 60° has access to the Io torus but because of the enhanced densities the rays are unable to propagate through the torus.

The frequency of the ray path calculations at 56.2 kHz (top panel of Figure 2) is chosen such that a direct comparison can be made with the observations of Jovian kilometric radiation from the plasma wave experiment on board Voyagers 1 and 2 (see companion paper by *Kurth et al.* [1980]). The ray tracing calculations at 56.2 kHz (top panel of Figure 2) show that at large radial distances (> 10 R_J) the shadow zone extends to approximately 13° magnetic latitude. *Kurth et al.* [1980] reported that Jovian kilometric radiation at 56.2 kHz is rarely observed at magnetic latitudes below 10°, thereby forming a shadow-like region. This good agreement supports the simple interpretation presented here that Jovian kilometric radiation is generated near Jupiter and not in or near the torus. Evidence for Jovian kilometric radiation generated in both the northern and southern hemispheres has been presented by *Gurnett et al.* [1979b]. It is easy to visualize the resulting illumination regions from southern hemispheric sources by the rotation of each panel in Figure 2 about the magnetic equator. The mixing of radiation inside the Io torus which has been generated from both hemispheres would result in the right- and left-hand polarized waves to be simultaneously observed (see below).

Ray tracing calculations at 800 kHz are shown in Figure 3. This figure illustrates the basic effects the Io torus has on ray paths at frequencies $\geqq$ 500 kHz. Rays with initial wave normal angles less than 58° (for this frequency) are confined to regions above the Io torus (also shown here as dashed lines). Note that the ray path labelled 48°, at radial distances > 9 R_J, penetrates closer to the magnetic equator than any other ray path with initial wave normal angle less than 58°. However, within 2° (from 58° to 60° rays) a sudden transition is made from strongly refracted rays to rays which are able to propagate almost directly through the Io torus. Most of the ray paths with initial wave normal angles greater than 60° are refracted by the torus such that at large radial distance (> 14 R_J) they are within a few degrees and nearly parallel to the magnetic equator. Unlike the ray paths for frequencies less than 500 kHz, the shadow zone is not a completely forbidden region for higher frequencies. However, very few rays are able to penetrate into the shadow zone since the torus spreads or defocuses the ray paths.

A summary of ray tracing calculations at frequencies $\geqq$ 200 kHz from source regions in the northern and southern hemispheres is shown in Figure 4. This figure shows the calculated ray path boundaries of kilometric radiation in and around the Io torus and illustrates that at radial distances > 10 R_J the latitude of the shadow zone increases with increasing frequency. This propagation effect is due in part to the placement of the source regions and would qualitatively be similar for any generation mechanism which requires successively higher frequency radiation to be generated at lower and lower Jovian altitudes. The ray path boundaries which are solid lines in Figure 4 are caustic ray surfaces where there is a build-up of wave intensity due to refraction effects. Note that the higher the wave frequency the deeper the radiation is able to propagate into the torus.

Since the closest approach of Voyager 2 to Jupiter was only about 10 R_J only Voyager 1 would have been able to observe Jovian kilometric radiation simultaneously generated from both hemispheres to frequencies as low as 100 kHz. From examination of Figure 4 the kilometric spectrum cutoff which should be observed by Voyager 1 can easily be predicted on the basis of the ray tracing calculations and is shown in Figure 5. In Figure 5, from about 0800 UT to about 1830 UT, Voyager 1 would have observed a filled bowl shaped feature in a frequency versus time spectrogram. Since emission from both hemispheres is assumed, the predicted kilometric spectrum during closest approach would, therefore, be composed of right- and left-hand polarized waves. The upper hybrid resonance frequency from the magnetospheric model used in this study is also shown in Figure 5 for comparison with the UHR emissions observed by Voyager. Only the planetary radio astronomy experiment is able to confirm these predictions since the upper frequency channel of the plasma wave experiment is only 56.2 kHz.

Discussion

The ray tracing calculations presented in this study are in very good qualitative agreement with the observations of Jovian

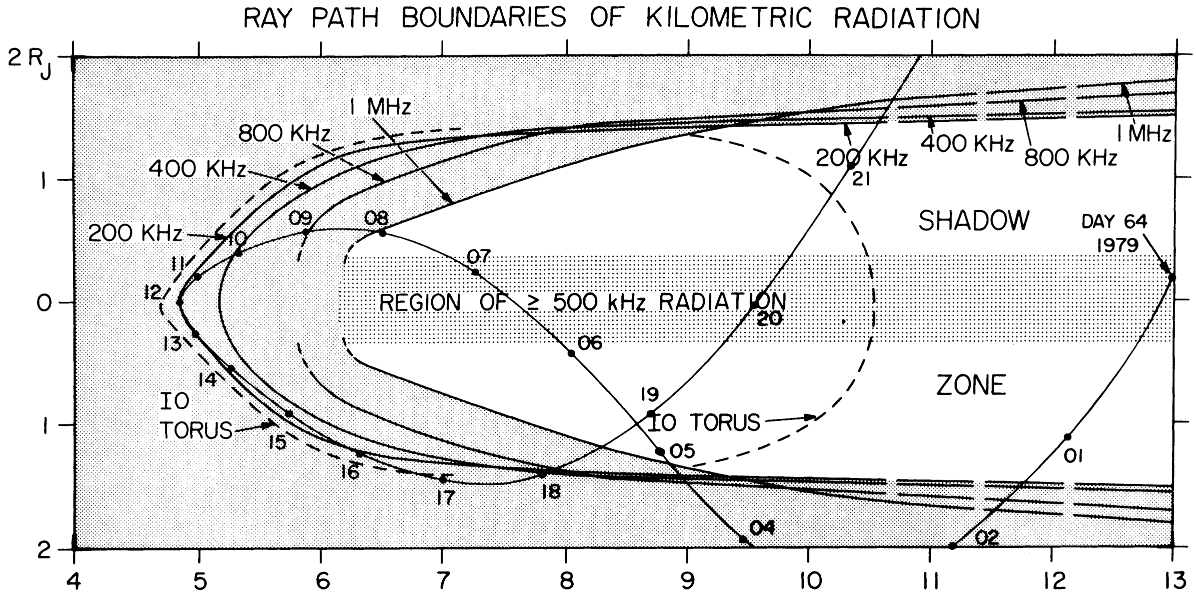

Fig. 4. Calculated ray path boundaries of kilometric radiation (at frequencies $\geqq$ 200 kHz) illustrating that at radial distances $\geqq$ 10 R_J the wave frequency increases as the latitude of the shadow zone increases. Also note that the higher the wave frequency the deeper the radiation is able to propagate into the Io torus.

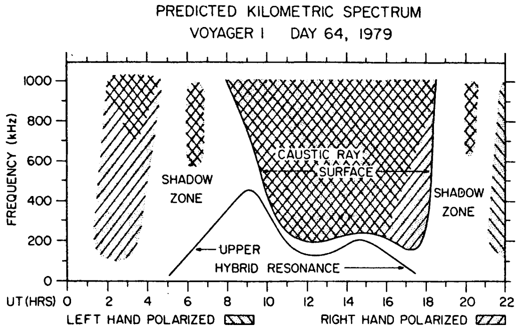

Fig. 5. Predicted spectrum of kilometric radiation observed by Voyager 1 near closest approach on day 64 of 1979.

kilometric radiation from the plasma wave receiver and the planetary radio astronomy experiment on board both Voyagers 1 and 2. First, it has been demonstrated that for a source region near Jupiter in the northern hemisphere a shadow zone is formed behind the Io torus that extends from the magnetic equator to approximately 13° magnetic latitude in good agreement with the observations of *Kurth et al.* [1980] at 56.2 kHz. Second, Figure 4 offers an explanation for the tapered events observed by *Warwick et al.* [1979] as a propagation effect introduced by the presence of the Io torus and the frequency dependent location of the source along a magnetic field line through the Io torus. In general at large radial distances, as the magnetic latitude of the spacecraft increases it is able to observe correspondingly higher and higher frequency radiation to a maximum of 1 MHz or more while still remaining within the illumination region of the lower frequency emissions (see Figure 4). Third, even though the present ray tracing study was limited to a two-dimensional magnetic meridian plane the results presented can easily be applied to three dimensions if the source regions were extended in longitude (possibly as much as 360°). Asymmetries observed in the tapered events reported by *Kurth et al.* [1980] can easily be accounted for by irregularities in the shape or height of the Io torus at different longitudes. Fourth, since in the ray tracing calculations the radiation was generated in the L-O mode from source regions near Jupiter, the observed polarization at large radial distances $\geqq 10\ R_J$ and at high northern magnetic latitudes would be left-hand in agreement with the observations. In addition, the results presented predict that Voyager 1 would have been able to observe Jovian kilometric radiation generated in both hemispheres only during and within a few hours of closest approach within the Io torus. At that time a mixture of right- and left-hand polarized waves would have been observed.

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